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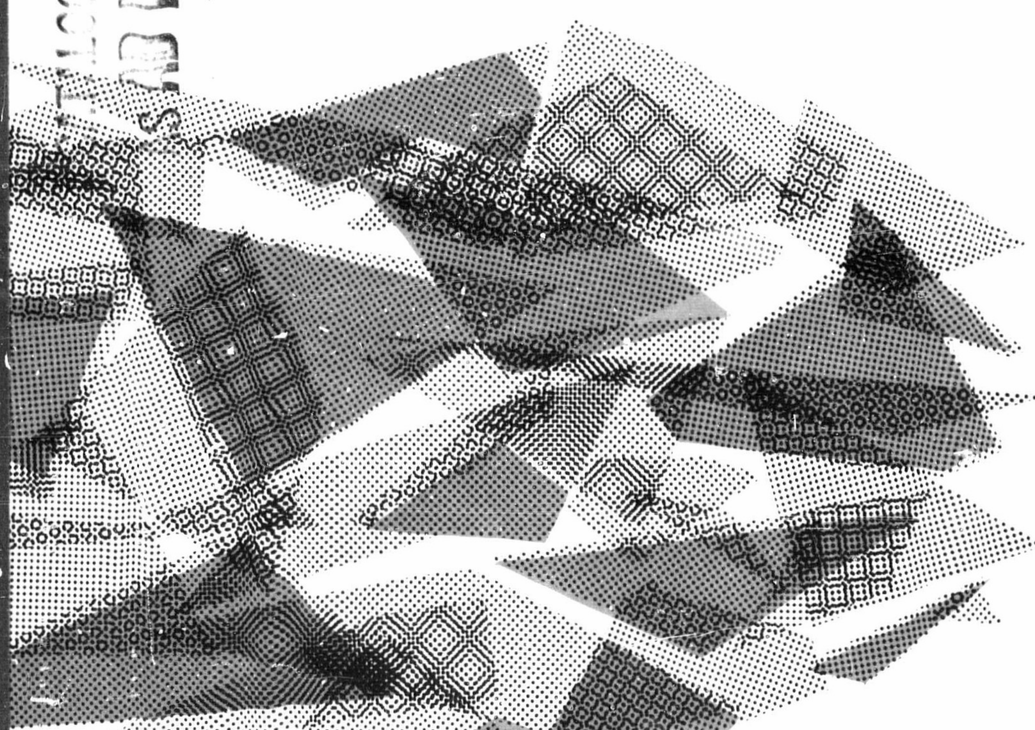
SPECIAL REPORT NO. S-70

HYBRID MOTOR CONCEPTS (I)–COMPONENT DEVELOPMENT AND REPRODUCIBILITY FIRINGS (U)



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HYBRID MOTOR CONCEPTS (I)—COMPONENT DEVELOPMENT AND REPRODUCIBILITY FIRINGS

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HYBRID MOTOR CONCEPTS (I)—COMPONENT DEVELOPMENT AND REPRODUCIBILITY FIRINGS

ABSTRACT

Eighteen successful firings of a 7 X 30 test motor were made with a concentric configuration of solid propellant and hybrid fuel grains. There were no hardware failures, and commercial injector nozzles and valves were used. Conventional rocket nozzle and chamber designs were satisfactory for hybrid use and standard insulation and ablative materials provided good protection of exposed hardware.

A piston expulsion device was developed and provided a reliable and reproducible method of pressurizing the oxidizer. A solid propellant gas generator provided a compact pressure source for driving the piston expulsion system.

The ratio of the booster phase thrust to the hybrid sustainer thrust exceeded 20. Combustion efficiency during hybrid operation was about 90% of theoretical.

The reproducibility of total impulse was poor in the hybrid phase. Combustion and injection processes appear to be inherently less reproducible than solid propellants. However, the solid-hybrid motor was not a good system for reproducibility measurements since the presence of the solid grain caused some difficulties in the partitioning of total impulse.

TABLE OF CONTENTS

Table of Contents continued

HYBRID MOTOR CONCEPTS (I)–COMPONENT DEVELOPMENT AND REPRODUCIBILITY FIRINGS

1. Introduction

Research in hybrid propulsion has been in progress for approximately 10 years with most of the work concentrated in the 1960-1965 period. The early work explored such phenomena as the mechanism of combustion and the interaction of fuel and oxidizer gases in the boundary layer; practicable regression rate laws were developed and verified in small test motors and the principles of interior ballistics and design were put into usable forms. This Division's work along these lines has been previously reported.[1]

In addition a good deal of empirical work has been done with oxidizer injectors, high-energy fuel additives, and gas stream mixers. Reasonable combustion efficiencies and specific impulses have been demonstrated in test motor firings.

Still lacking, however, was the "know-how" of hardware components such as injectors, valves, controls, and nozzle materials, and the application of pressurization systems to hybrid motors. A two-thrust-level rocket motor consisting of a solid propellant booster and a hybrid sustainer was used to develop these components and to demonstrate one type of application of interest to the Army. This report summarizes the results of an investigation begun in June 1964.

2. Requirements

In order to give the program direction and meaning a useful Army propulsion system was chosen as the basis for this study. The resulting requirements were aimed at demonstrating:

(a) the combination of a solid propellant booster with a hybrid sustainer in a single chamber;

(b) boost-to-sustain thrust ratio of 20 to 1;

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[1] Rohm & Haas Company, Quarterly Reports on Interior Ballistics, P-63-1, October 1963; P-63-8, January 1964; P-63-15, March 1964; P-63-22, June 1964; P-64-1, June 1964; P-64-8, July 1964; P-64-15, August 1964; P-64-22, November 1964.

(c) satisfactory ignition of both grains and the transition from booster to sustainer operation;

(d) satisfactory chamber and nozzle design;

(e) containment, pressurization, valving, and metering of the liquid oxidizer;

(f) the use of a solid propellant gas generator for pressurization.

Also specified were nitrogen tetroxide as the oxidizer and a carboxy-terminated polybutadiene binder, with appropriate additives, as the hybrid fuel. The sustainer operating time was to be a minimum of 16 seconds.

Light-weight hardware was to be used to facilitate design of flight-weight components at a later date. However, in areas where light-weight components could cause delays, heavier designs were acceptable. An additional requirement, added after the program was underway, was that the motor be capable of precise cut-off so that thrust termination characteristics and total impulse reproducibility could be determined.

3. Initial Design Studies

3.1 Design of Booster and Sustainer Charges

The O. D. of the booster grain was fixed at 6 inches to allow preliminary testing with available hardware; an L/D of 5(30-inch length) was chosen as a convenient size for handling. Motor operating pressures of 2000 psia during boost and 125 psia during sustain were established to provide the 20 to 1 thrust ratio. The burning times of each mode were: boost, 1 to 2 seconds; sustain, 16 seconds minimum. Use of a carboxy-terminated polybutadiene binder was specified for both grains.

Single chamber operation with one nozzle was chosen for simplicity. To achieve both a compact unit and a sustainer fuel grain of reasonable length the booster charge was placed inside and concentric with the sustainer charge. These constraints required that trade-offs be made between the burning surfaces and rates of the two grains and that the nozzle throat be properly sized—large enough to permit a reasonable sustainer mass flow and small enough to avoid the problems of high throat-to-port area ratio during boost.

The initial port diameter and length of the sustainer were fixed by the O.D. and length of the booster grain. Theoretical calculations showed that the optimum impulse of the sustainer would be at an oxidizer/fuel ratio of about 2.2 to 2.4. Since no regression rate data were available for the carboxy-terminated polybutadiene binder, experimental data were used for a polybutadiene acrylic acid material. The increase of the sustainer port diameter with time was determined at o/f ratios of 2.2 and 2.4 as a function of nozzle throat area using the continuity equations and the fuel regression rate expression

$$r = \xi (MP)^{0.6}$$

where ξ = a constant, dependent on fuel properties

M = Mach number

P = chamber pressure.

At a chamber pressure of 125 psia, the fuel regression rate is higher for the larger throat diameters, and thicker webs are necessary to achieve the 16-sec burning time (Fig. 1).

The booster grain design was based on a chamber pressure of 2000 psia and the P-K-r relationships available for a typical, high-energy propellant formulation using carboxy-terminated polybutadiene binder. The burning rate, throat-to-port area ratio, and burning time were plotted as a function of nozzle throat area for several possible booster geometries (Fig. 2). The AG and AO configurations were available from previous work, while AY was designed specifically for this use (Fig. 3). A throat area of 2.5 sq. in. was selected, which specified the burning rate of the booster propellant (0.5 in/sec). For convenience, the sustainer O.D. was taken as 7.0 inches, which required a regression rate of 0.03 in/sec at an MP

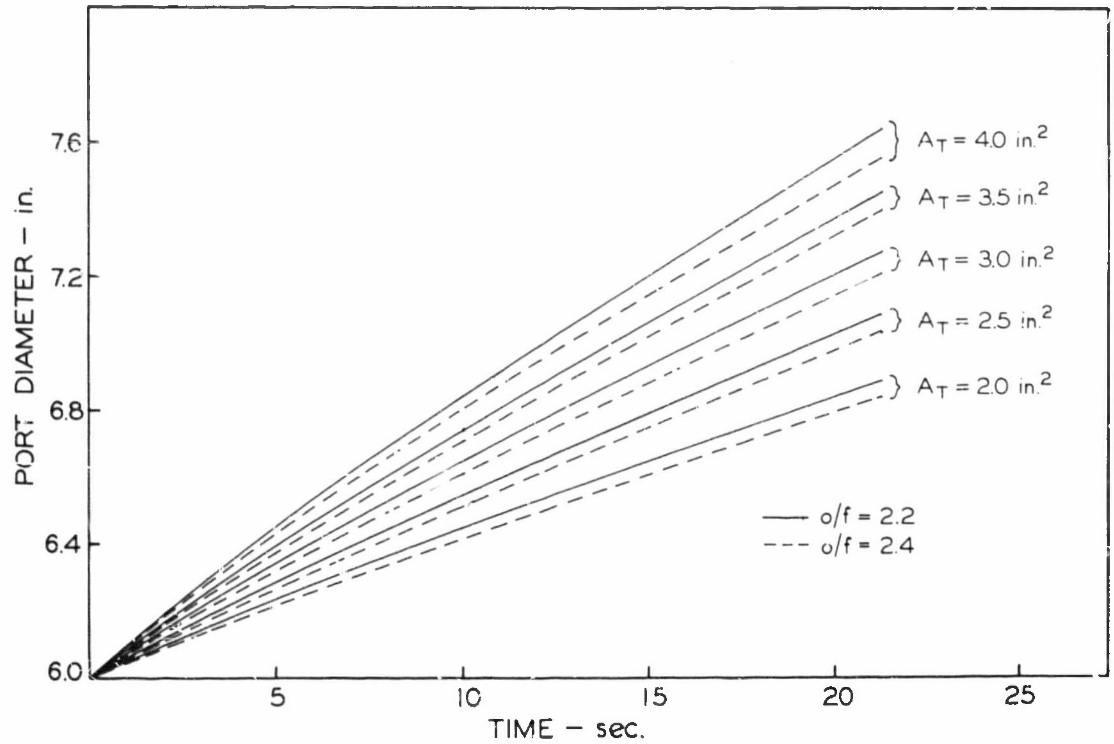

Fig. 1 Port diameter of sustainer grain as a function of time and throat area at a chamber pressure of 125 psia.

product of 7. The combination of booster and sustainer grains gives a volumetric loading fraction of 0.735. Motor performance is summarized in Table I.

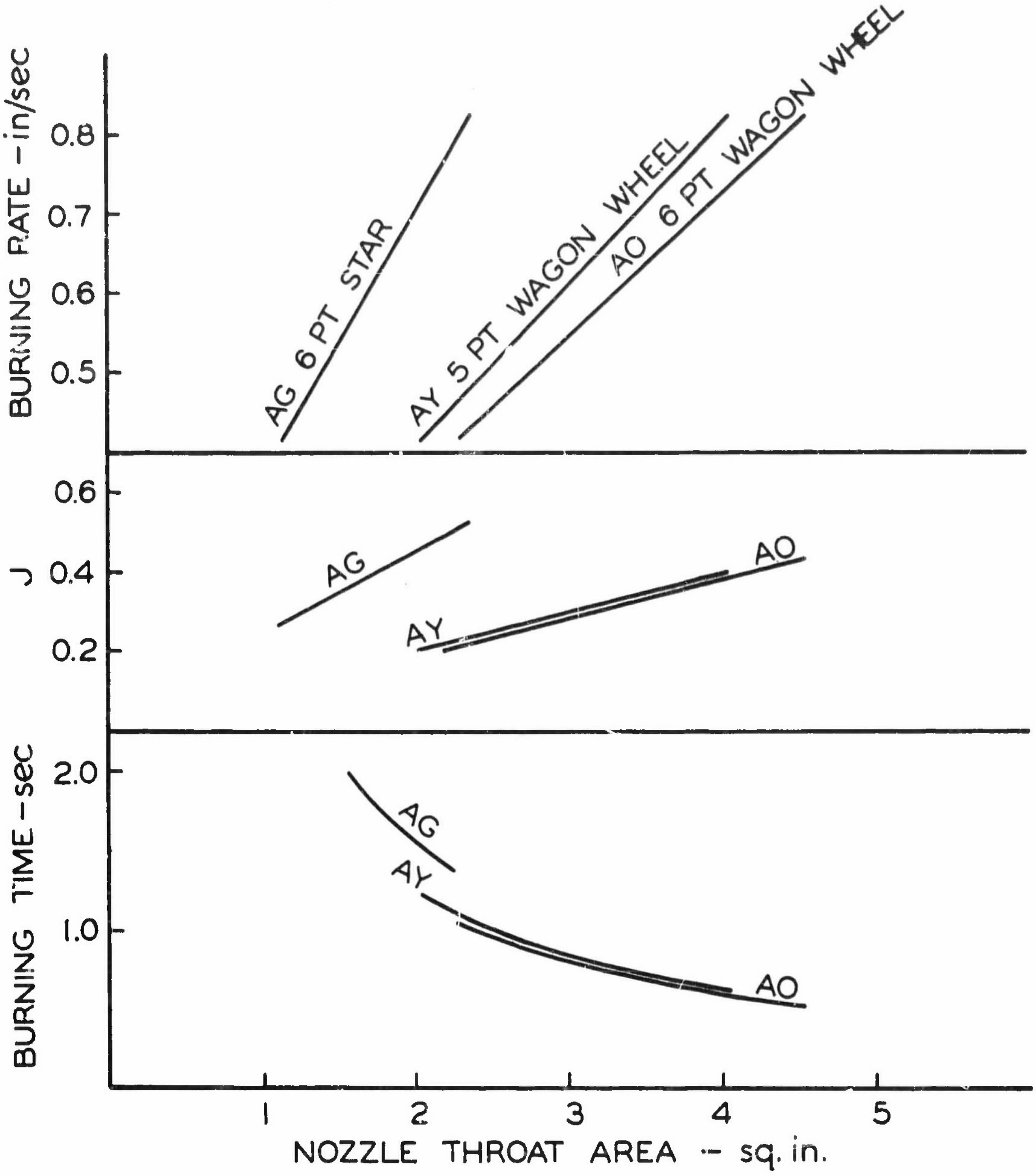

Fig. 2 Calculated design parameters for several booster grain geometries.

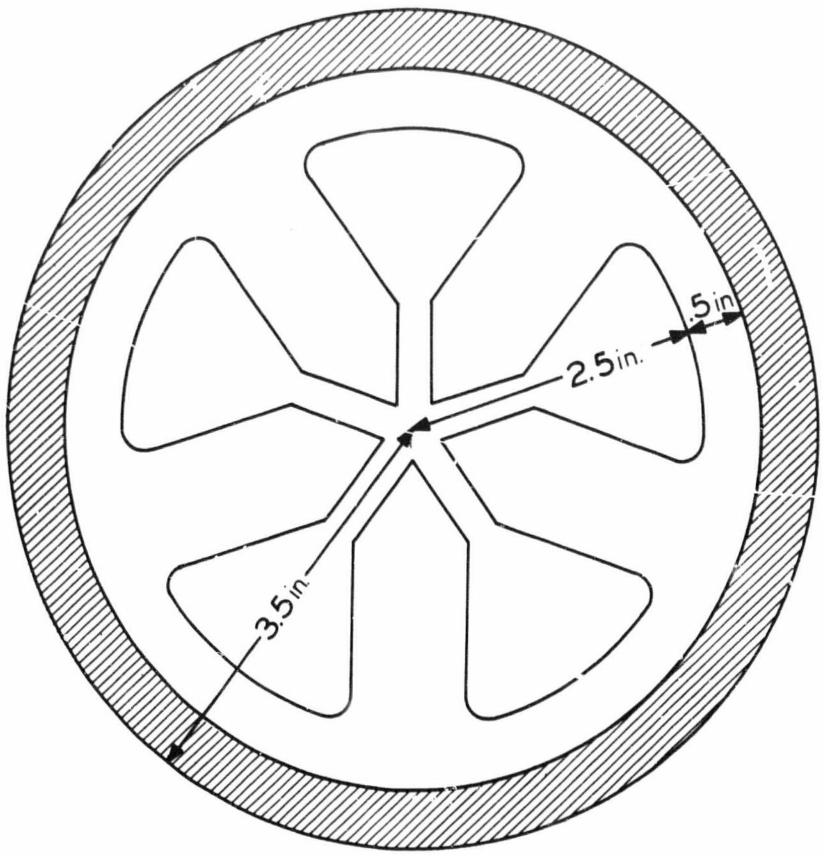

Fig. 3 AY booster grain and circular sustainer grain.

Table I

Design Characteristics of 7 X 30 Hybrid Motor

	Booster	Sustainer
Thrust, lbf	8000	400
Burning time, sec	1.0	16.0
Chamber pressure, psia	2000	125
Propellant weight, lbm	35	10 fuel, 20 oxidizer
Grain design	5 pt. wagon wheel	Cylindrical
Loading fraction	0.64	0.265
	Overall 0.735	

4. Propellants for the Hybrid Motor

4.1 Development of Sustainer Fuel

Carboxy-terminated polybutadiene binder containing different percentages of ammonium perchlorate were fired in 2 X 7.5 motors using gaseous oxygen as the oxidizer. The regression rates were determined from the weight lost during firing. A plot of the regression rate as a function of the MP number indicated that the oxidizer content did not influence the regression rate significantly at percentages below 30%; the slope was 0.8 (Fig. 4). The fuel became self-sustaining with more than 30% oxidizer, and fuels with oxidizer precentages approaching 30 had considerable afterburning even though they did eventually extinguish. As a reasonable compromise between high density, non-sustaining characteristics, and minimum afterburning, a fuel with 15% ammonium perchlorate was chosen for the hybrid motor sustainer. No aluminum was used because it was felt that it would be difficult to burn with the simple mixer available.

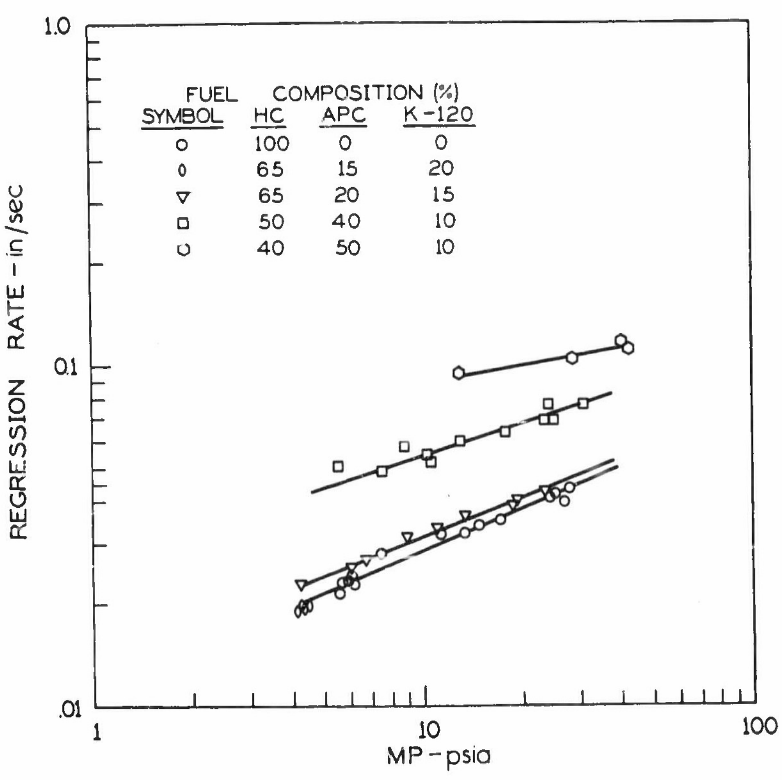

Fig. 4 Effect of ammonium perchlorate content on regression rate of hybrid fuels.

Early casting experience with the 15% ammonium perchlorate - 85% binder fuel showed severe settling problems. Acryloid®[1] K-120 acrylic powder was added to the fuel to increase its initial viscosity and prevent settling. After some compositional studies a level of 20% acrylic powder was chosen and the final fuel composition was designated RH-C-17 (Table II).

Table II

Composition of Hybrid Fuel RH-C-17

Ingredient	%
ZL-434[a]-MAPO-ERLA	64.0
Ammonium Perchlorate	15.0
Acryloid® K-120	20.0
Iron Linoleate	1.0

[a]A carboxy-terminated polybutadiene, Thiokol Chemical Corporation, Trenton, New Jersey

The regression rate of RH-C-17 was lower than the design rate of the sustainer because the expected increase in rate due to addition of ammonium perchlorate did not materialize. This lower rate shifted the o/f ratio to approximately 4 and caused a slight degradation in impulse (Fig. 5). The low regression rate in the hybrid motor firings is due in part to the cooling effect of the evaporating liquid oxidizer. Figure 6 is a composite plot of regression rate of GOX and hybrid motor firings.

4.2 Development of Booster Propellant

4.2.1 Initial Formulation Work

The boost portion of the hybrid component development motor required a propellant having a burning rate of approximately 0.5 in/sec at 2000 psia. A carboxy-terminated polybutadiene composition (RH-C-2) containing different ammonium perchlorate particle sizes was fired in 2C1.5-4 motors; burning rates ranged from [illegible]1 to 0.59 in/sec at 2000 psia.

[1] Trademark for acrylic ester polymers, Rohm & Haas Company, Philadelphia, Pennsylvania.

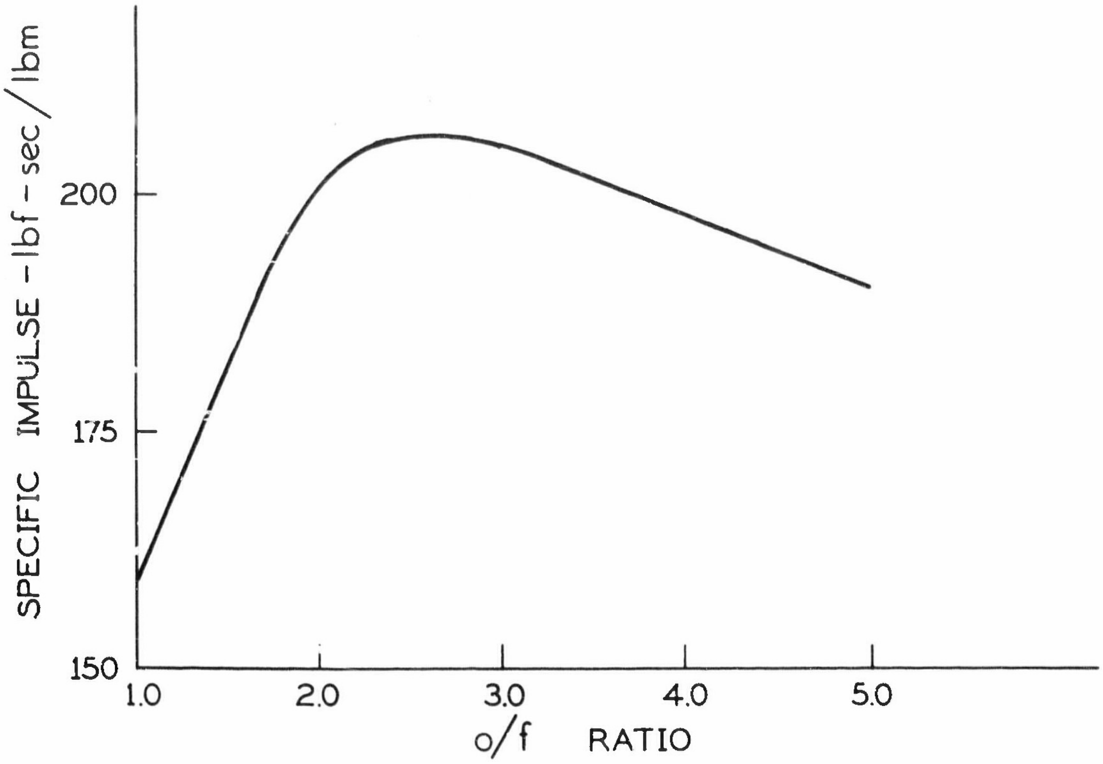

Fig. 5 Calculated specific impulse for N_2O_4 and RH-C-17 at a chamber pressure of 1[illegible].5 psia.

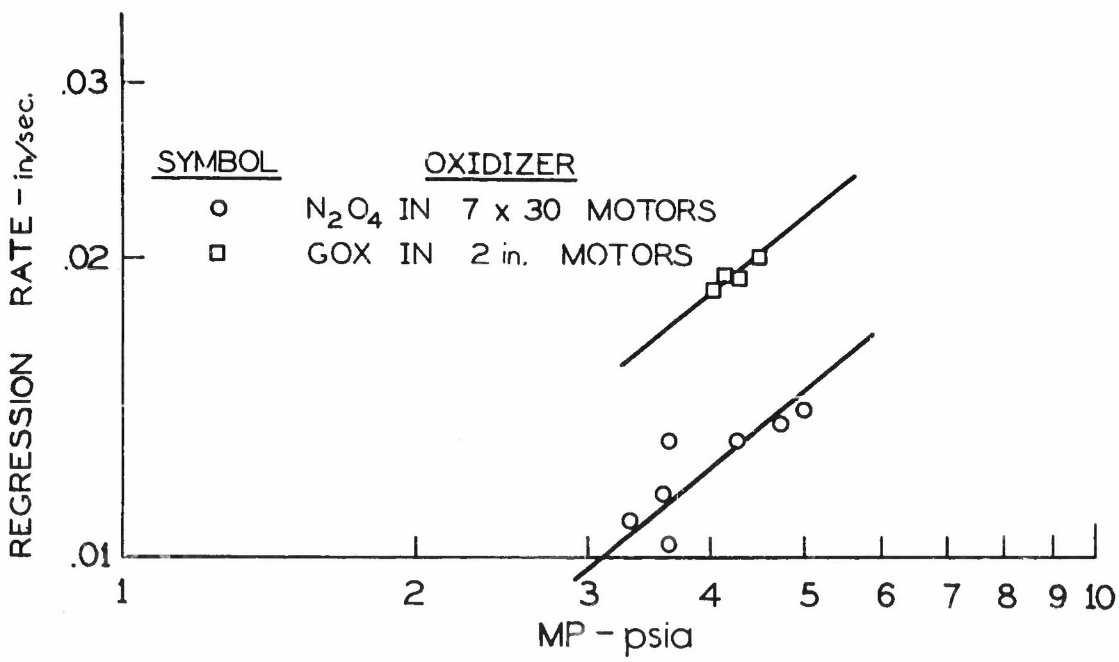

Fig. 6 Comparison of regression rate of RH-C-17 fuel with gaseous oxygen and liquid N_2O_4.

From a plot of burning rate as a function of particle size, the composition containing 55% ce and 45% cc oxidizer was chosen (Fig. 7). The composition and some properties of this propellant are shown in Table III.

4.2.2 Final Booster Propellant

The initial booster propellant contained a plasticizer, dioctyl adipate, to reduce the initial mix viscosity. However, early bonding tests between booster and sustainer grains revealed that substantial amounts of plasticizer migrated from booster propellant to the sustainer fuel, which was unplasticized. Subsequently, the booster propellant cracked severely.

This problem was solved by developing an unplasticized composition RH-C-20 (Table IV). Its burning rate was lower than the design burning rate of 0.5 in/sec. A small adjustment in nozzle throat diameter was made to keep the average chamber pressure near 2000 psia

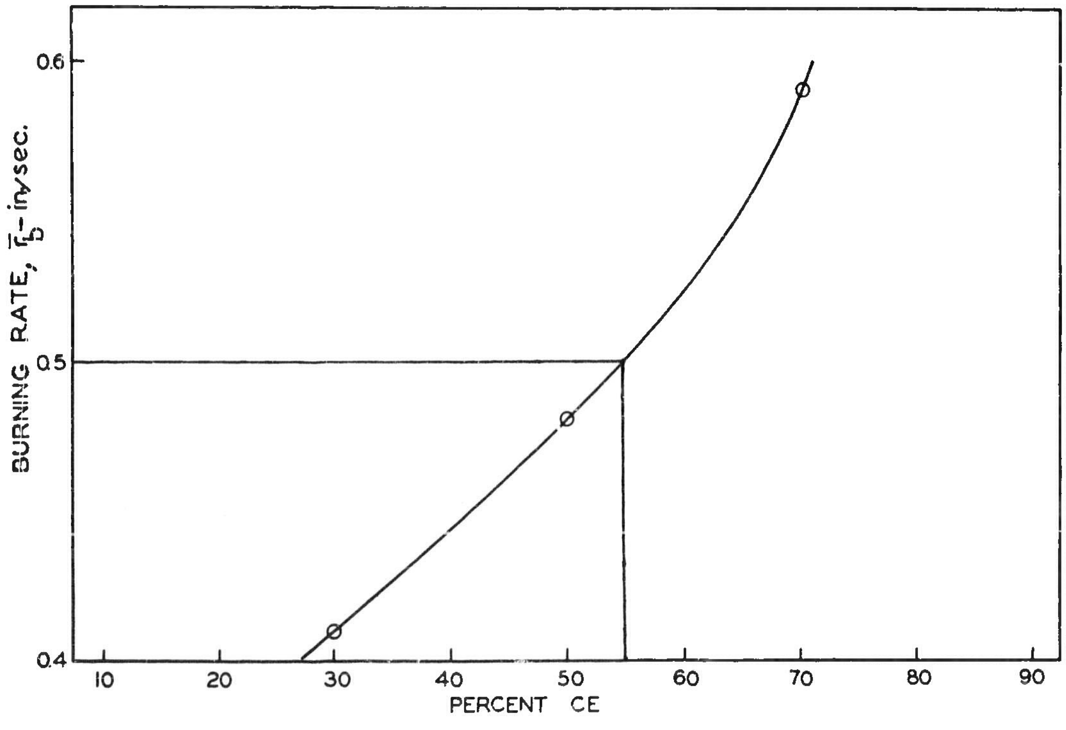

Fig. 7 Effect of ammonium perchlorate size on the burning rate of RH-C-2 at 2000 psia.

instead of making further propellant compositional changes and the design thrust was lowered slightly.

Table III

Characteristics of Booster Propellant Candidate RH-C-2

Ingredients	%
ZL 434-MAPO-ERLA	10.1
Ammonium Perchlorate	68.9
Aluminum	16.0
Dioctyl adipate	5.0
Propellant Properties	
Theoretical I_{sp}, lbf-sec/lbm	261
Density, lb/in^3	0.064
Tensile strength, psi, 77°F	75-100
Elongation, %, 77°F	20-30

Table IV

Composition RH-C-20

Ingredient	%
ZL434-MAPO-ERLA	15.65
Ammonium Perchlorate	68.00
Aluminum	16.00
Ferrocene	0.25
Iron linoleate	0.10

Evaluation of the booster grain configuration and propellant composition was carried out in 6-inch static test motors to establish ignition characteristics, operating pressure, burning time, and tail-off characteristics. Although the booster charge was designed to be slightly progressive, the resultant pressure trace was somewhat regressive due to erosive burning and pressure drop (Fig. 8). Otherwise, the records and resulting data were as expected (Table V).

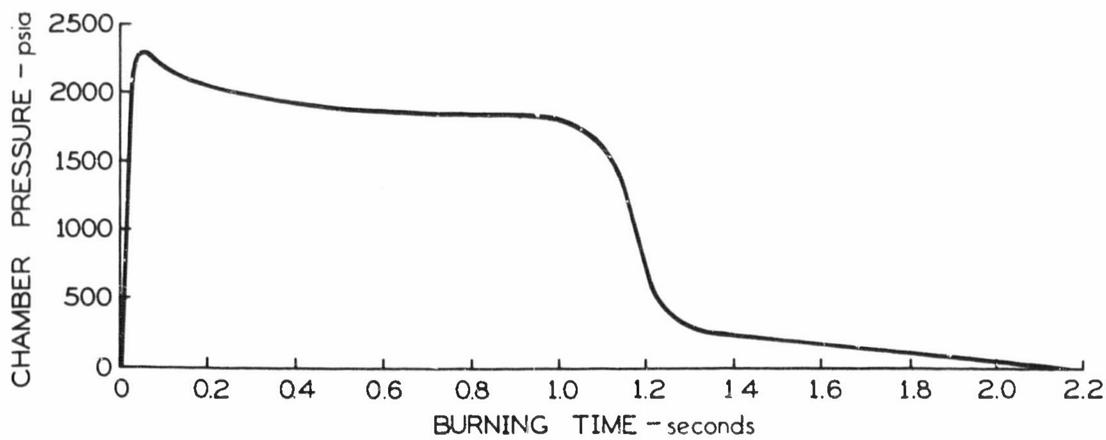

Fig. 8 Pressure trace of booster grain (Round 3120).

Table V

Ballistic Data from Booster Grain Firings with RH-C-20 Propellant

Round No.	K_m	t_b msec	$\bar{r}_b$ in/sec	$\bar{P}_b$ psia	$\frac{\int P_b dt}{\int P_t dt}$	F^0_{1000} lbf-sec/lbm
3102	400.1	1169	0.428	1626	0.92	242.9
3119	404.1	1144	0.437	1618	0.89	242.9
3120	459.9	1125	0.445	1898	0.89	241.5
3175	458.1	1024	0.488	2029	0.89	240.7[a]
3176	464.2	1076	0.465	1977	0.88	243.2
3177	468.1	1031	0.485	2125	0.88	243.2

[a]This propellant batch had a low aluminum content and a high perchlorate content.

5. Details of Inert Hardware

The following sections describe various aspects of the motor hardware design.

5.1 Motor Chamber

The motor case was fabricated of cold-drawn steel tubing and had an inner diameter of 7.0 inches. The head-end closure was a flat, stainless steel plate that was drilled for 12 oxidizer passages and a pressure port. Snap rings were used to hold the head-closure and nozzle in place and O-rings provided the pressure seal. The relatively heavy wall was needed to hold the high pressure booster phase. A thrust harness was attached at the forward skirt. Fig. 9 shows the details of the design. The insert shows the overall aspect of the assembled motor and ozidizer tank.

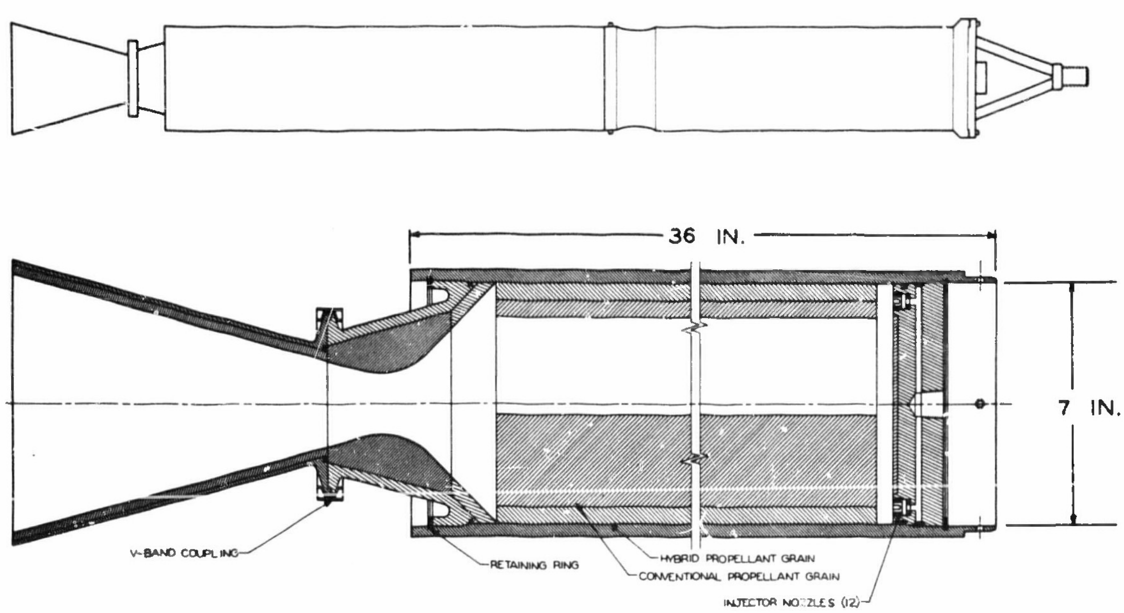

Fig. 9 Hybrid motor case, injector plate, and nozzle assembly.

5.2 Oxidizer Injectors

The injector system injected 12 fan-shaped streams in the circle of the sustainer grain's internal diameter. The resulting spray pattern was a hollow cylinder of oxidizer particles located adjacent to the burning surface (Fig. 10). This configuration was chosen in place of a single injector because of evidence that an oxidizer-rich core promotes combustion instability. Components from standard commercial spray injectors[1] were used.

5.3 Mixer Plate

The use of devices to mix the gas flow in the combustion chamber of hybrid motors has been shown to markedly increase the combustion efficiency. The more effective devices have a complex geometry to change the

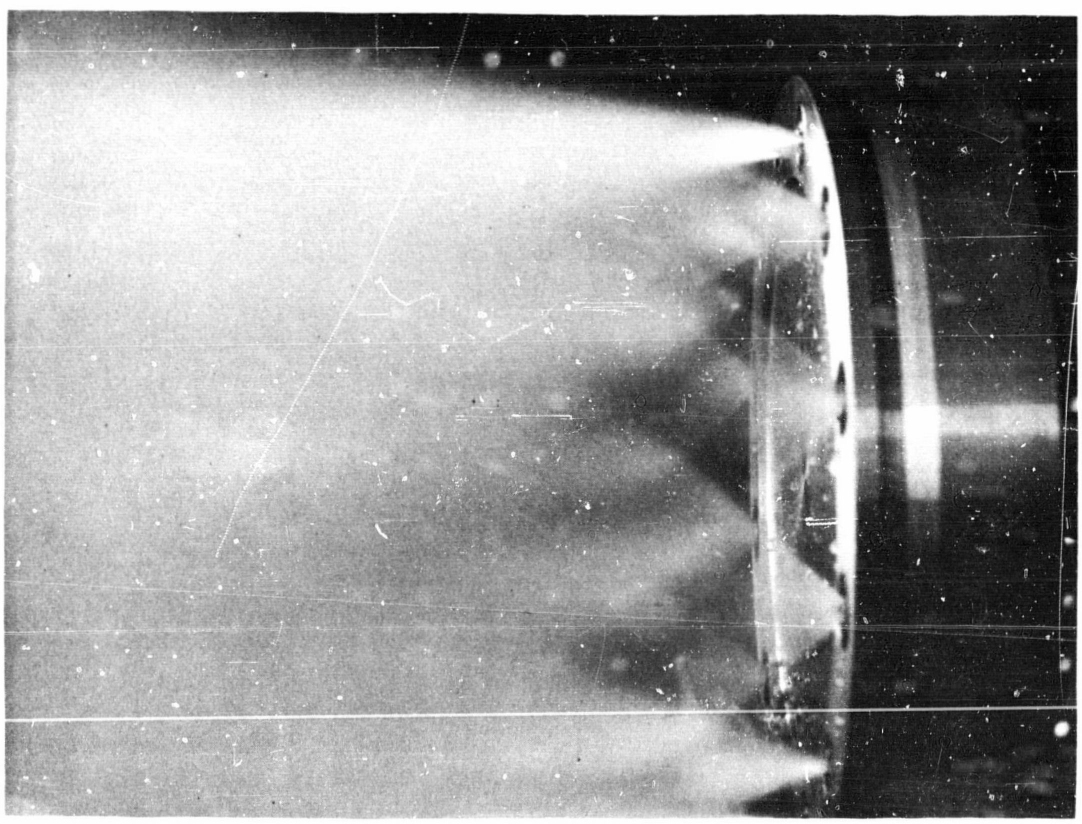

Fig. 10 Injector plate and spray pattern for 7 × 30 motor.

[1] Unijet Nozzle $\frac{1}{4}$TT8003, Spraying Systems Company, Bellwood, Illinois.

gas flow direction and induce good mixing; large pressure drops are usually present. In the 7 X 30 hybrid motor however, the mixer was a ½-inch thick, 42-RPD[1] plate which had the shape of the booster grain (Fig. 3). It was bonded to the aft-end of the grain and held in place by the nozzle. The high mass flow rate from the booster phase precluded use of a more efficient design.

5.4 Motor Nozzle

The motor nozzle was basically a large graphite insert in a steel housing. A snap ring held the nozzle in the case and an O-ring provided the pressure seal. The converging face of the nozzle was insulated with asbestos phenolic to protect the steel against erosion. Test results showed that the nozzle design was conservative and that there were no special problems during hybrid operation. The nozzle diameter normally increased about 0.05 in. during a shot.

Nozzles for single-chamber dual-thrust motors pose a special problem with regard to the selection of a proper expansion ratio. If a fixed nozzle expansion ratio is used, delivered impulse of either the booster or sustainer phase will be degraded depending on whether the expansion ratio is high or low.

This problem was solved by building an exit cone that was large enough to adequately expand the booster propellant gases but that separated at a diameter suitable for proper sustainer expansion. A V-clamp held the large extension in place during firing and an explosive bolt removed the clamp after booster operation (Fig. 9).

6. Oxidizer Pressurization Systems

6.1 Features of Piston Expulsion System

The piston expulsion system for the 7 X 30 hybrid motor was designed to expel 25 in^3/sec of liquid N_2O_4 at a pressure of 500 psia. Fig. 11 shows the details. The oxidizer tank or cylinder had an inner

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[1] A molded asbestos-phenolic material, Raybestos-Manhattan Company, Manheim, Pennsylvania.

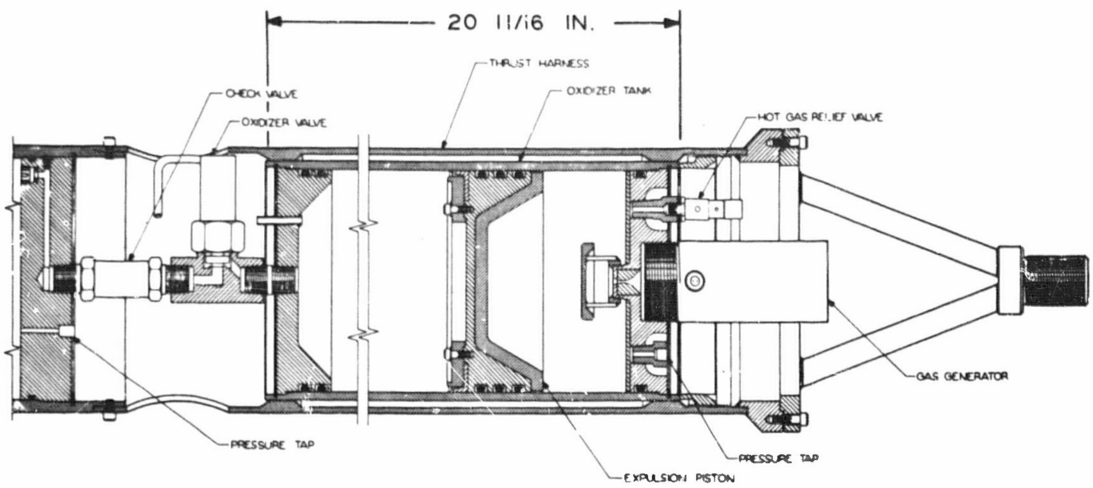

Fig. 11 Hybrid oxidizer tank and pressurizing system.

diameter of 6.5 inches and was constructed of 6061-T6 aluminum tubing; the inner surface was hand-polished to a 16 micro-inch finish. Snap rings were used to hold the flat-plate end closures.

The piston itself was 6061-T6 aluminum and had a generous length-to-diameter ratio of 0.5. The Teflon®[1] cup seal located on the oxidizer side was backed up by two Viton A®[2] O-rings seals; a silicone rubber O-ring was used on the hot-gas side because of its heat-resisting properties. Standard engineering tolerances were used on the piston, cylinder and O-ring clearances. The O-ring materials were not compatible for long-term storage with N_2O_4 but were satisfactory for short periods.

The face of the piston was insulated with a layer of Paraplex®[3] P-13 - ground asbestos material to reduce heating, and the flow from the

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[1] Trademark for tetrafluoroethylene (TFE) fluorocarbon resins, E. I. duPont de Nemours & Co., Inc., Wilmington, Delaware.

[2] Trademark for a fluoroelastomer, E. I. duPont de Nemours & Co. Inc., Wilmington, Delaware.

[3] Trademark for unsaturated polyesters that cure to a cross-linked structure, Rohm & Haas Company, Philadelphia, Pennsylvania.

solid-propellant gas generator was deflected to prevent direct impingement on the piston face.

The gas-side pressure was regulated with a commercial hot-gas relief valve.[1]

6.2 Evaluation of the Piston Expulsion System

The piston expulsion system performed very well in all respects. Tests with water on the liquid side and regulated nitrogen gave excellent reproducibility of flow rate (Table VI). The pressure differential across the piston due to friction was about 60 psi.

Table VI

Flow Rates of Water with Piston Expulsion

Run	Nitrogen Pressure (psia)	Mass Flowed (lbm)	Time (sec)	Flow Rate (lbm/sec)
1	494.4	17.36	21.15	0.821
2	487.7	17.45	21.27	0.820
3	484.4	17.41	21.35	0.815
4	487.7	17.43	21.35	0.817
5	484.4	17.42	21.41	0.814
6	484.4	17.41	21.39	0.814
7	487.7	17.42	21.43	0.813
8	481.1	17.42	21.50	0.810
9	484.4	17.43	21.46	0.812
10	481.1	17.44	21.52	0.810
	485.7	17.42	21.38	0.815

Fourteen tests were carried out in which N_2O_4 was expelled by hot gas or regulated nitrogen; there were no leaks or malfunctions. The gas generator contaminated the honed surfaces of the cylinder with small solid particles which had to be wiped off before reuse. In the reproducibility

[1] Pyronetics, Inc., Santa Fe Springs, California.

tests nitrogen was the pressurizing gas and the piston could be returned to the initial position without cleaning or replacing seals. Oxidizer cut-off occurred when the piston reached the limit of travel.

The tank pressure was regulated by a hot gas relief valve set to dump gas overboard when the tank pressure exceeded 500 psig. Due to the restricted capacity of the relief valve, the hot gas generator was sized to fill the expulsion needs with a small excess to assure pressurization.

Several trials were necessary to size the hot gas generator for the proper flow rate. A 2-inch diameter generator was too large and overloaded the relief valve. After one test in which a $1\frac{1}{2}$-inch gas generator proved inadequate, the diameter was adjusted to $1\frac{3}{4}$ inches.

The piston expulsion system provided a reliable and reproducible method of pressurizing the N_2O_4 oxidizer for hybrid motor tests.

6.3 Features of Direct Expulsion System

The simplest way of expelling N_2O_4 oxidizer from a tank is by direct pressurization with the hot gases from the gas generator. However, there is a possibility of an uncontrolled reaction between the oxidizer and the hot reducing gas.

The tank designed and fabricated for direct expulsion tests was a welded stainless steel vessel with pressure ports, fill lines, and a special adapter for the gas generator (Fig. 12). A gas diffuser was mounted in the top of the tank to prevent impingement of the hot gases into the liquid oxidizer.

6.4 Results of Oxidizer Expulsion by Direct Pressurization

Preliminary tests of direct pressurization of N_2O_4 with hot gas were carried out in heavy-wall hardware (Fig. 13). Of primary interest was the nature of the reaction between the hot gas and N_2O_4; there were small pressure peaks on the initial pressurization of the N_2O_4 tank but no large peaks or over pressures (Fig. 14). The hot-gas relief valve[1] regulated the pressure to 500 psig plus or minus 25 psi when not overloaded.

[1] Pyronetics, Inc., Santa Fe Springs, California.

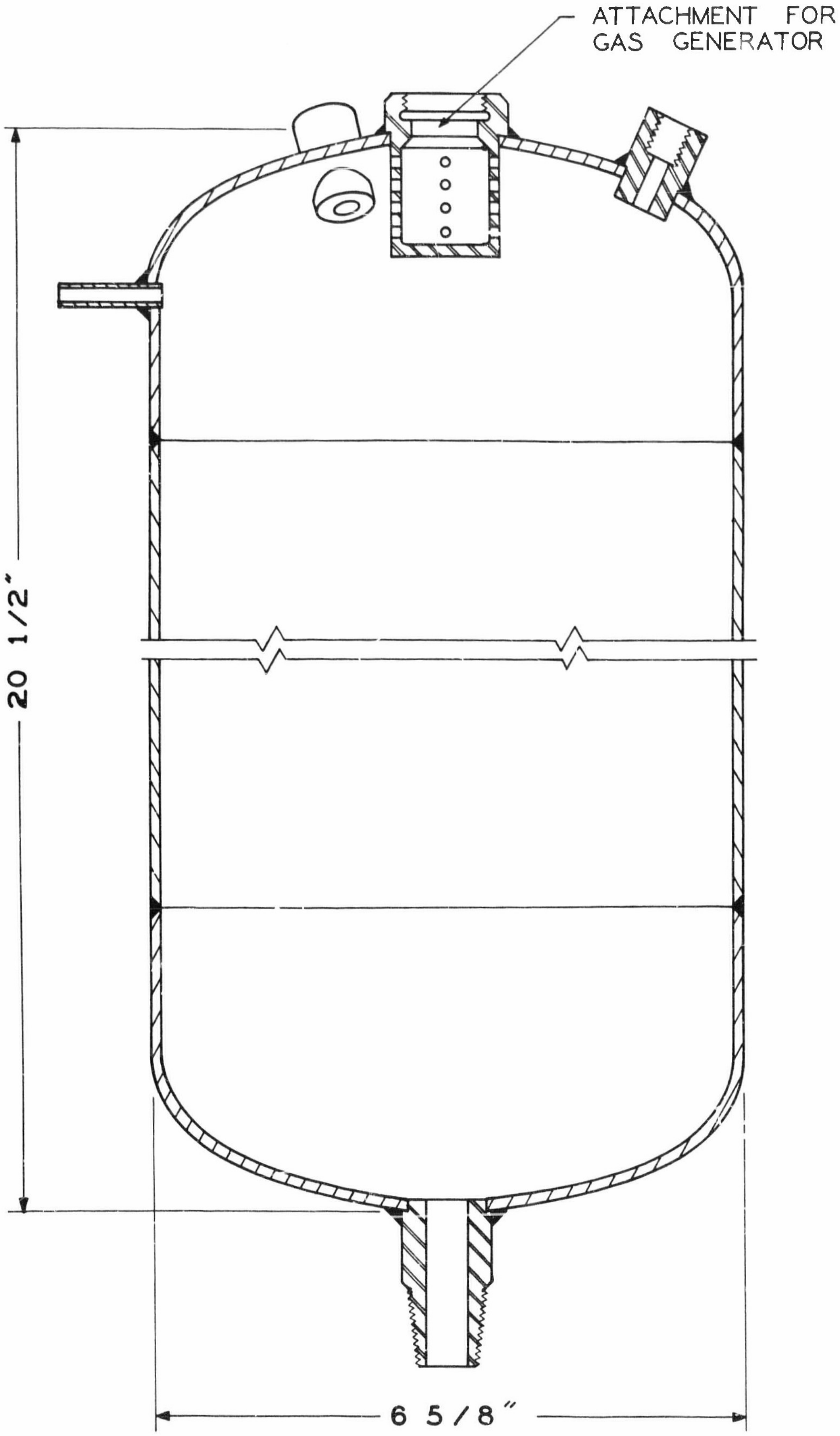

Fig. 12 Medium weight tank for direct pressurization tests.

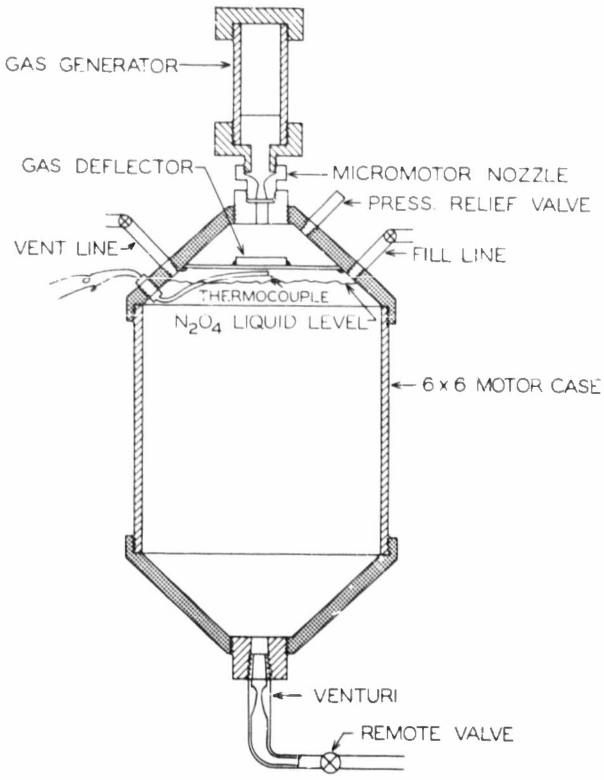

Fig. 13 Arrangement of heavy weight equipment used for tests of gas-generator expulsion of N_2O_4.

The physical condition of the relief valves was good after each shot with only slight carbon buildup on the seat and each valve was reused at least one time. Thermocouple measurements indicated that gas temperature reached a maximum of 2000°F in the tank while tank wall temperatures remained 150°F. The tank wall temperature was not significant, however, owing to the heavy weight.

Sizing the gas generators required the empirical approach. A heavy-wall direct pressurization system was first tested with water as the fluid. The combined cooling effect of the water and the long flow passages required a gas generator grain diameter of 2 inches for full pressure. However, in the identical system, the extra gas from the N_2O_4 hot gas reaction overloaded the pressure relief valve. A $1\frac{1}{2}$-inch gas generator was used on subsequent direct expulsion and found satisfactory.

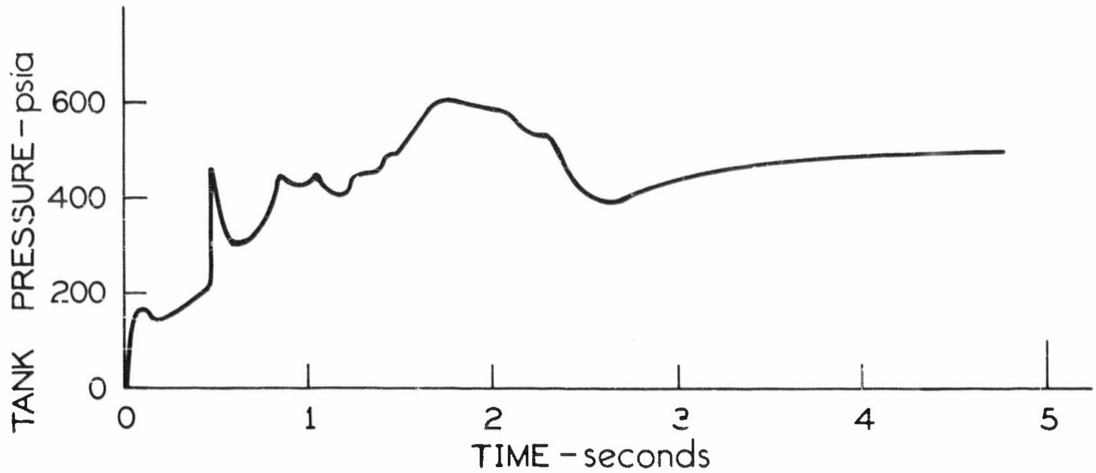

Fig. 14 Tank pressure vs. time for direct pressurization of N_2O_4 by hot gas.

Tests with the medium-weight tank (Fig. 12) were characterized by smooth pressurization to regulated pressure of 500 psig and constant pressure operation for approximately 2 seconds. This phase was terminated by a very sudden pressure peak and subsequent burning of the relief valve seats. Movies showed that the relief valves were dumping relatively cool gas before the pressure peak and very hot gas after the peak. The tank pressure dropped to zero after the peak. This reaction was reproducible in three tests.

It was concluded that direct pressurization by hot gas is potentially a light, simple method for pressurizing liquid oxidizers such as N_2O_4 in missiles having a continuous, positive acceleration. One tank geometry used in this program caused explosive mixtures of N_2O_4 vapors and hot gas to build up and react violently. A heavy-wall tank of different geometry apparently produced a continuous reaction which prevented build-up. The scope of the present program did not permit further development of a reliable hot-gas direct pressurization unit.

6.5 Auxiliary Equipment

The remainder of the oxidizer expulsion system consisted of a stainless steel main cutoff valve,[1] a stainless steel check valve,[2] and the injector head (Fig. 11). On some early developmental tests the pressurization system consisted of a tank that was directly pressurized with nitrogen gas, a cavitating venturi for flow control, a flowmeter[3] for flow measurement, a pressure gauge, and a thermocouple in addition to the check valve and injector head.

7. Development of a Solid-Propellant Gas Generator

The pressurizing gas generator for the N_2O_4 oxidizer used a cylindrical end-burning charge. Small nozzles were used to regulate pressure and mass flow rate (Fig. 15). Composition RH-P-298, the gas generator propellant chosen for this application, has a theoretical flame temperature of 2271°F at 1200 psi and an exhaust temperature of 1776°F at 500 psi. The composition and some properties of this propellant are shown in Table VII.

A number of preliminary tests were made using RH-P-298 in a 1.5-inch diameter end-burning charge. The propellant was cast directly into the motor cases and good bonding was achieved with a thin cellulose acetate lacquer. Plugging of the small nozzle throat with solid combustion products was the most serious problem encountered. This was

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[1] Model HY473, Hoke, Inc., Cresskil, New Jersey.
[2] Model 459-½ SS2-65, Republic Manufacturing Co., Cleveland, Ohio.
[3] Model ½-81T3A1, The Foxboro Company, Van Nuys, California.

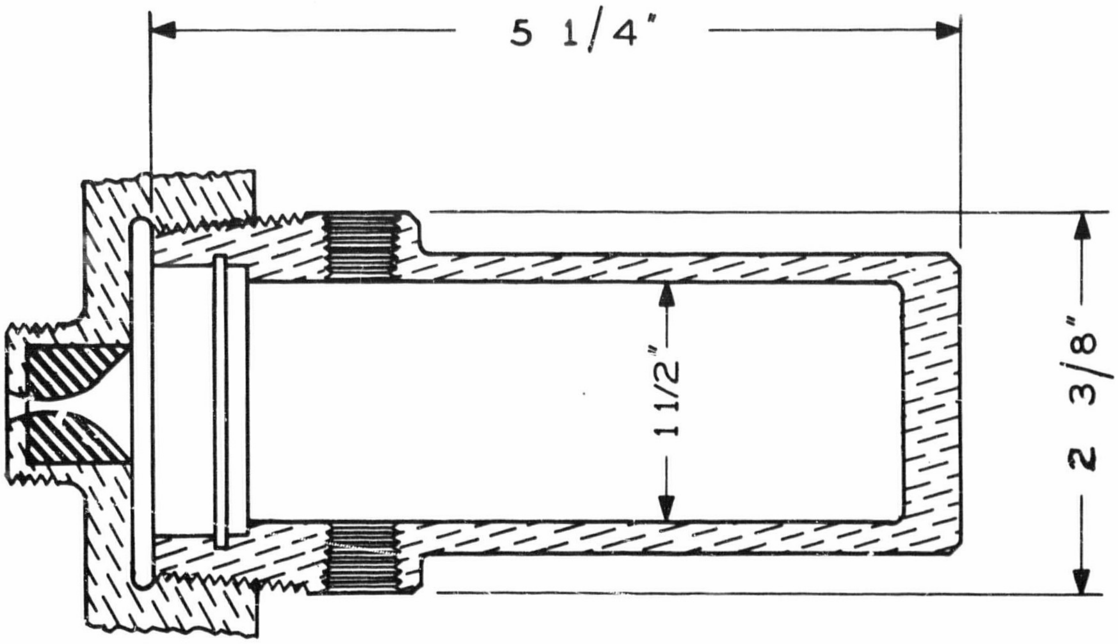

Fig. 15 Details of 1.5-inch gas-generator hardware.

eliminated by installing metal filters consisting of thin steel plates with 100-0.029" holes ahead of the 0.043-inch nozzle throat. Good ignition and excellent pressure trace were achieved (Fig. 16).

Since the volume of gas required for pressurization depends greatly on the configuration and heat loss, final sizing of the generator was carried out concurrently with the expulsion tests. This is reported in Sections 6.2 and 6.4.

The use of a sonic nozzle to control the mass flow from very small gas generators is a "second-best" method. If very close tolerances are not held on the nozzle throat diameter, a wide variation in operating pressure and mass discharge rate will result. Conventional machining limits of ±0.002 inches in a diameter of 0.043 are not adequate for precise control. A second disadvantage is the need for filter screens. A nozzle of this size can easily be plugged by foreign material and hence cause erratic operation of the gas generator.

Table VII

Characteristics of Gas Generator Propellant RH-P-298

	%
Double-base powder	15.0
Triethyleneglycol dinitrate	43.0
RDX	25.4
Oxamide	12.1
Lead stearate	3.5

Propellant Properties

Theoretical flame temperature, °F (1200 psia)	2271
Theoretical exhaust temperature, frozen flow, °F (500 psia)	1776
Average mol. wt.	20.7
$\overline{r}_b$ at 1200 psi, in/sec	0.18
Density, lbm/in^3	0.055

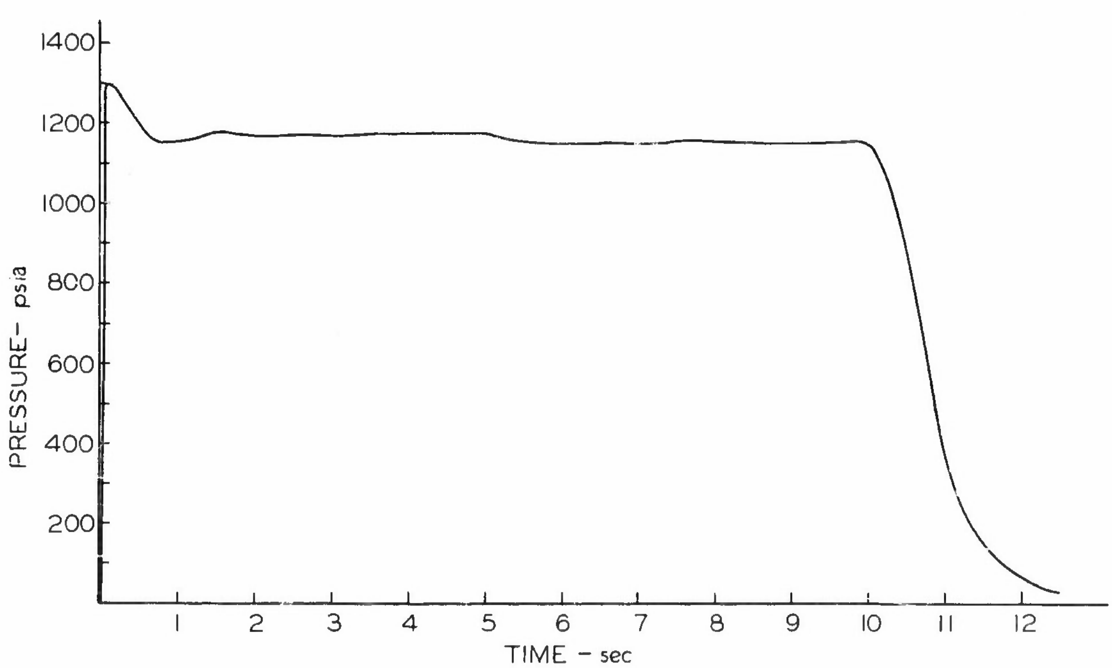

Fig. 16 Firing trace from 1.5-inch diameter gas generator.

A more suitable system would use a propellant with plateau burning characteristics. The mass generation rate would be controlled by the grain diameter and no sonic nozzle would be used.

8. Results of Motor Firings

8.1 Sustainer Firings

No 7 × 30 motors were fired solely for the booster grain evaluation. However, four initial firings were made with the sustainer grain to check the operation of the injectors, pressurizing system, and motor hardware. The burnout of the booster grain was simulated by bonding slivers of a plastisol nitrocellulose composite propellant to the sustainer surface. These slivers gave a pressure trace similar to the tail-off of the booster grain and provided ignition of the motors. Regulated high-pressure nitrogen pressurized the oxidizer.

In these first firings the chamber pressure was about 70 psia, substantially below the 125 psia desired (Table VIII). The low regression rate of the fuel accounted for this effect (Fig. 6). All hardware performed satisfactorily and a reasonably clean combustion gas was exhausted through the nozzle. The nozzle expansion ratio was 2.3.

Some exploratory tests were run on different oxidizer injection systems in an attempt to raise the combustion efficiency. A single-hole, full-cone injector gave a combustion efficiency of 84%, which was less than the average efficiency with the standard configuration (Table VIII, Round 4161). Similar results were obtained when a small amount of high-pressure, gaseous nitrogen was injected with the N_2O_4 to help break up the oxidizer droplets. However, nitrogen injection in the 12-hole configuration did raise the impulse to 92% (Round 4163). The quantity of nitrogen used in these tests was small, about 0.016 lbm per lbm of oxidizer and this might be a practical technique.

8.2 Booster—Sustainer Firings

A total of eighteen dual-grain firings were made with the 7 × 30 motor; ten of these were made to study reproducibility of total impulse (See Section 8.3).

Table VIII

Summary of Hybrid Sustainer and Booster-Sustainer Firings

	Booster Phase			Sustainer Phase						
Round	t_b sec	$\overline{P}_b$ psia	$\overline{F}_b$[a] lbf	t_b sec	$\overline{P}_b$ psia	$\overline{F}_b$[b] lbf	I_{spd} lbf-sec/lbm	F^{v}_{125} lbf-sec/lbm	η %	Remarks
3118	-	-	-	17.1	67	-		-	-	No thrust
3121	-	-	-	10.5	120	-	-	-	-	No thrust
3128	-	-	-	17.9	69	-	-	-	-	No thrust
3182	-	-	-	17.2	73	190	137	171	82	
3296	1.05	1940	-	16.3	102	-	-	-	-	Piston expulsion + gas generator
3371	1.08	1894	5652	20.8	100	265	178	186	95	Piston expulsion
3411	1.08	1873	6255	17.0	109	278	174	183	94	Piston expulsion
3446	1.09	1880	6287	17.7	116	280	166	172	87	Piston expulsion + gas generator
3610										Direct pressurization with gas generator; relief valve failed after 4 sec. No useful motor data.
3611										
3612	-	-	-	18.4	71	154	140	172	88	Sustainer only
3484	1.07	1912	6050[c]	-	-	-	-	-	-	Oxidizer valve did not open
3485	1.07	1902	6406	16.3	121	346	162	162	80	
3936	1.10	1882	6003[c]	16.9	120	394	202	204	99	
3937	1.09	1921	6487	16.3	115	362	185	188	94	
4161	-	-	-	10.4	76	169	144	170	84	1-hole, full-cone injector
4162	-	-	-	9.89	67	138	127	159	83	1-hole Injector + N_2
4163	-	-	-	10.07	75	159	148	176	92	12-hole injector + N_2
4164	-	-	-	-	36	69	-	-	-	1-hole Injector-poor ignition

[a] Nozzle expansion ratio was 20
[b] Nozzle expansion ratio was 2.3
[c] Estimated values

In general, the dual-grain firings were very successful. The average pressures and the burning times of the booster phase were quite reproducible; the $\overline{F}_b$ values were determined by measuring the thrust burning time (Table VIII). The nozzle expansion ratio was about 20.

The transition from booster operation was smooth and the ignition of the hybrid grain was good in all firings. On some shots the oxidizer valve was opened while chamber pressure was higher than the oxidizer tank pressure. The check valve prevented flow until the pressures equalized and a gradual transition occurred with no inflection point in the pressure trace (Fig. 17). Opening the valve when the chamber pressure was below 500 psia caused a definite pressure rise but no sharp peaks or overpressures occurred.

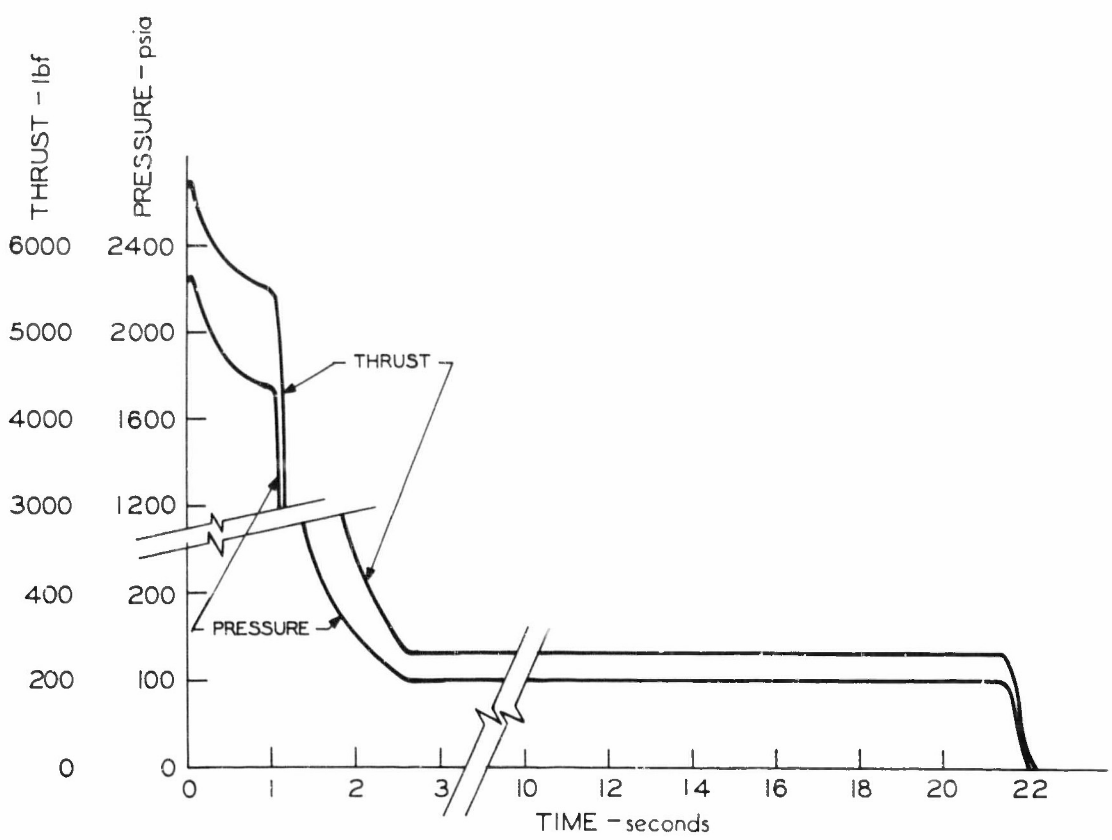

Fig. 17 Typical thrust and pressure traces for the 7 X 30 solid-hybrid motor (Round 3371).

The chamber pressures in the first firings were below the design value of 125 psia. Oxidizer flow rates were gradually increased on later shots to compensate for the low fuel regression rates and the sustainer pressures approached the design value of 125 psia (Rounds 3485, 3936, 3937). This caused operation at a non-optimum o/f ratio of about 4. The mean pressure was constant during a hybrid firing, but there were some oscillations; the amplitude was typically 20 psi.

Average thrust of the booster was approximately 6200 lbf while the sustainer thrust has ranged from 150 to 400 lbf depending on the oxidizer flow rate and the chamber pressure.(Table VIII). The thrust ratio of 20/1 was adequately demonstrated. Although not specifically tested in a single motor, some throttling capability was demonstrated as shown by the range in sustainer thrust values.

Piston expulsion of the oxidizer was used on four of these eight firings with good results and a gas generator was the pressure source in two of these tests. On shots using piston expulsion, the large pressure drop across the injector and the maximum design pressure of the piston tank limited the flow rates, and hence the sustainer chamber pressure tended to be low, about 100 psia. (Rounds 3296, 3371, 3411, 3446).

On dual-grain shots the detonator that removed the clamp on the nozzle expansion cone was fired concurrently with the opening of the oxidizer valve. When the valve was opened before booster burnout, the expansion cone was held in place by the pressure forces until over-expansion occurred. In every case separation was very gentle and no significant thrust peaks were noted.

Specific impulse efficiency of the hybrid sustainer averaged 89% but ranged from 80 to 99%. The average value agrees with performance figures reported by other organizations for hybrid motors having little or no gas stream mixing. The efficiency was calculated by correcting the specific impulse of a firing to standard conditions at 125 psia and comparing that value with a computer-calculated value at the same conditions, including o/f ratio.

Partial flooding of the fuel grain surface could explain some of the variation in efficiency. There was non-uniform gouging of the grain extending about 4 inches downstream from the injector, which indicates poor combustion. The rest of the grain regressed uniformly.

The accuracy of the sustainer thrust measurement was degraded by use of the 10,000-lbf load cell. One side of a dual-bridge 10K load cell was set to measure the booster thrust and the other side was set to measure the sustainer thrust. Even with the gauge set up for maximum sensitivity, the accuracy was poor. A similar problem existed with the pressure measurement since a 2000 psi pressure gauge was set up to maximum sensitivity to give readings during sustainer operation at 125 psia.

Data reduction on the 7 X 30 motor was complicated by the transition period during which both booster and sustainer propellants were burning. Two approaches were used to reduce the data of these first firings. In the first procedure the delivered impulse of the booster propellant determined in 6AY33 motors was subtracted from the total impulse of the 7 X 30 motor and the remainder attributed to the hybrid sustainer. This method did not account for the booster slivers burning at a higher pressure due to the hybrid oxidizer injection. The extra impulse would show up in the sustainer impulse. The second method consisted of dividing the sustainer average thrust by the propellant mass flow rate to get a specific impulse. This method had the disadvantage that the fuel flow rate was difficult to determine owing to the transient period during booster tail-off. Of the two techniques, the first is probably more accurate.

8.3 Reproducibility of Total Impulse and Thrust Termination

Ten 7 X 30 motors (solid propellant booster and hybrid sustainer) were fired to investigate the reproducibility of total impulse.

8.3.1 Description of Special Equipment and Procedures

Special care was taken with each round to get identical firing conditions and accurate measurements of the pressure, thrust, and weights. Before firing, the booster grain was trimmed to a fixed length; the mass burned was 32.59 lbm with a standard deviation of 0.3%.

An overload protection device was obtained to permit a 1000 lbf load cell for sustainer thrust measurements to be placed in series with the 10K load cell. After a significant baseline shift on Round 4190, this unit performed as intended.

A 750 psia pressure cell rated to withstand a 300% overload was used to measure pressure during sustainer operation. The gauge was not linear up to booster pressure and a serious baseline shift occurred.

To protect the gauge, a valve was installed between it and the chamber. It was opened as the oxidizer flow was started.

The weight of oxidizer injected was held to a constant value by using a full charge in the piston expulsion tank.

The data reduction procedure was also modified. The booster impulse was measured from ignition to the thrust pip that occurred from the start of oxidizer injection. This time was nominally 1.3 seconds (Fig. 18). The sustainer impulse was the total impulse less the booster impulse.

8.3.2 Results of Test Firings

The burning times and average pressures of the boost phase were consistent and the standard deviations were 1.8% and 2.1% respectively (Table IX). The standard deviation for the total impulse was greater than is typical for solid motors, but part of this variation may be caused by the procedure for assigning impulse to the booster and sustainer phases. For this reason, the dual-thrust hybrid motor was not the best type for reproducibility studies.

The oxidizer injector pressure was quite uniform and good control of flow rates might be expected. However the injector pressure drop, not a cavitating venturi, controlled the flow rate and some differences were seen. Since the weight of oxidizer loaded in the tank was very consistent, (See M_o column) the burning time is a measure of the flow rate; control was not as good as was desired.

The burning time, operating pressure, and thrust level showed a wide difference from round to round. However, the sustainer impulse itself did not vary as much as might be expected. The 8.3% standard deviation reflected the close control on oxidizer weight and the large o/f ratio. The combustion efficiency was again low, about 90%. The low specific impulse was due, in part, to the low operating pressure. Table IX summarizes the results for the important parameters.

The total impulse for the 7 X 30 motor averaged 12803 lbf-sec with a standard deviation of 2.6% for the eight good rounds (Table X).

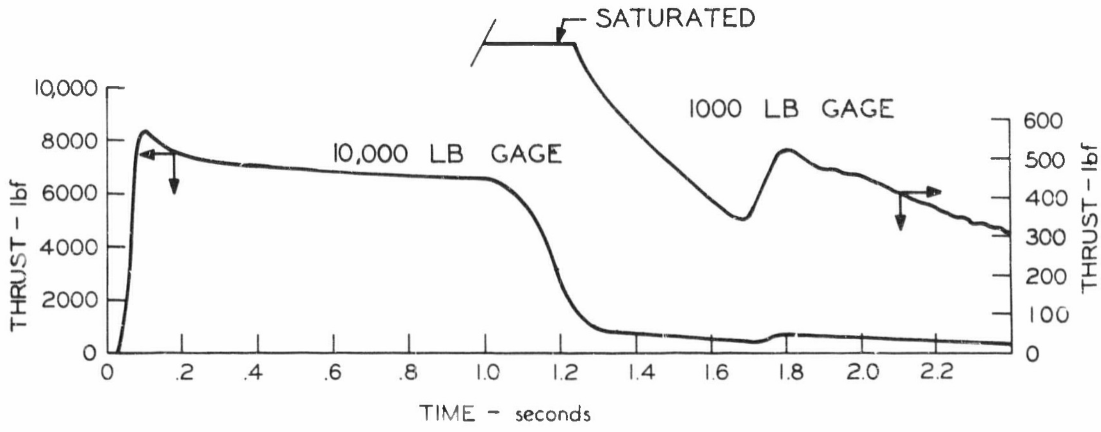

Fig. 18 Thrust vs. time for 7 X 30 motor with late oxidizer injection (Round 4192).

This lower variation was not unreasonable, considering the somewhat arbitrary division of impulse between booster and sustainer. The relatively long thrust cut-off times were a result of the ammonium perchlorate in the fuel since some slight after-burning occurred. A completely inert grain should show much faster cut-off times.

Table IX

Summary of Solid-Hybrid Motor Firings for Impulse Reproducibility

Booster Phase

Round	t_b sec	$\overline{P}_b$ psia	$\overline{F}_b$[a] lbf	I lbf-sec	M_p lbm	F^0_{1000} lbf-sec/lbm
4190	1.02	2125	6988	8030	32.73	245.3
4191	1.00	2055	6989	8039	32.55	247.0
4192	1.04	2024	6845	7966	32.59	244.4
4193	1.02	2015	7026	7952	32.65	243.6
4311	1.01	2035	6904	7846	32.77	239.4
4402	1.02	2059	7017	7946	32.57	244.0
4403	1.02	2045	7012	7929	32.59	243.3
4467	1.04	2006	6858	7924	32.52	243.7
4469	1.00	2061	6988	7758	32.51	238.6
4470	1.06	1962	6598	7772	32.46	239.4
Average	1.02	2039	6922	7916	32.59	242.9
σ	0.02	43	132	96	0.10	2.8
$\%\sigma$	1.86	2.1	1.9	1.2	0.3	1.2

Sustainer Phase

Round	Oxidizer Pressure psia	t_b sec	$\overline{P}_b$ psia	$\overline{F}_b$[b] lbf	I lbf-sec	M_o lbm	M_f lbm	$\dot{m}$ lbm/sec	I_{spd} lbf-sec/lbm	F^0_{125} lbf-sec/lbm	o/f	η %
4190[c]	509	27.61	63.6	215	5945	24.74	8.198	1.193	180.5	232.5	3.02	113
4191	507	22.12	67.2	183	4067	24.24	5.327	1.337	137.5	171.9	4.55	89
4192	507	22.79	73.5	221	5064	24.37	7.026	1.378	161.3	193.4	3.47	96
4193	485	19.22	102.0	250	4828	24.25	5.780	1.562	160.8	171.8	4.20	88
4311	483	19.97	87.3	308	4786	24.70	5.590	1.517	158.0	177.3	4.42	91
4402	485	20.72	98.2	235	4897	24.80	5.725	1.473	160.4	173.2	4.33	89
4403[d]	516	17.09	80.6	194	3416	15.25	5.010	1.185	168.6	194.6	3.04	95
4467	520	17.67	114.0	281	5000	25.85	5.690	1.755	161.5	167.6	4.45	86
4469	506	21.38	102.0	259	5509	24.45	7.650	1.502	171.8	183.5	3.20	90
4470	487	20.33	102.0	248	5069	24.65	5.720	1.493	167.1	178.5	4.31	92
Average	500	20.53	93.3	248	4902	24.66	6.063	1.502	159.8	177.2	4.12	90
σ	14	1.61	16.0	38	405	0.52	0.816	0.126	10.0	8.2	0.50	3
$\%\sigma$	2.7	7.84	17.1	15.1	8.3	2.1	13.4	8.4	6.3	4.6	12.1	3.3

[a] Nozzle expansion ratio was about 20
[b] Nozzle expansion ratio was 2.3
[c] Large baseline shift in sustainer load cell; sustainer phase values not included in averages
[d] Tank was not completely full of oxidizer; sustainer phase values not included in averages

Table X

Reproducibility of Total Impulse for the 7 X 30 Solid-Hybrid Motor

Round	Booster Impulse lbf-sec	Sustainer Impulse lbf-sec	Total Impulse lbf-sec	Thrust Cut-off Time[a] msec
4191	8039	4067	12106	335
4192	7966	5064	13030	70
4193	7952	4828	12780	305
4311	7846	4786	12632	310
4402	7946	4897	12843	275
4467	7924	5000	12924	440
4469	7758	5509	13267	210
4470	7772	5069	12841	355
Average	7900	4902	12803	288
σ	99	405	338	110
$\%\sigma$	1.3	8.3	2.6	38.2

[a] Time is interval from t_b calculated on the thrust trace to the time at 10% $\overline{F}_b$ for the sustainer.

9. Summary

All objectives of the component development program for hybrid rocket motors were met. Eighteen successful firings of the 7 X 30 test motor demonstrated that a concentric configuration of solid propellant and hybrid fuel work well together, giving thrust ratios exceeding 20. There were no hardware failures, and commercial injector nozzles and valves were used. Conventional rocket nozzle and chamber designs were satisfactory for hybrid use. The separating exit cone provided optimum expansion during both booster and sustainer operation.

Piston expulsion provided a reliable and reproducible method of pressurizing the oxidizer. A solid propellant gas generator provided a compact pressure source for driving the piston expulsion system.

The hybrid fuel was based on a carboxy-terminated polybutadiene binder containing 15% ammonium perchlorate. Regression rates were lower than expected and the fuel tended to burn for a short time after oxidizer flow ceased. Combustion efficiency during hybrid operation was about 90% of theoretical. Large variations in oxidizer flow rate resulted from using injector pressure drop to control the flow. Better control would result from using a higher oxidizer pressure and a cavitating venturi ahead of the injectors.

The reproducibility of total impulse of the hybrid phase was poor. Combustion and injection processes appear to be inherently less reproducible than solid propellants. However, the solid-hybrid motor was not a good system for reproducibility measurements since the presence of the solid grain caused some difficulties in the partioning of the total impulse.

10. Future Work - Tandem Solid-Hybrid Motor for Zoning Demonstration

The original hybrid program has been extended to include design and testing a solid-hybrid combination which will demonstrate the feasibility of a simplified method of zoning. It is anticipated that this program will culminate in several flight firings to demonstrate zoning by thrust termination.

A single-chamber motor with the hybrid fuel grain and solid-propellant grain in tandem configuration was conceived to meet this need. The hybrid grain is located in the head-end, the solid charge is placed at the nozzle-end, and a simple mixer plate separates the two grains. The solid propellant charge thus acts as an igniter for the hybrid grain, and the volume vacated by the solid propellant serves as a large mixing chamber to increase hybrid combustion efficiency. In operation the solid propellant charge burns for 2 seconds and the hybrid phase follows immediately and provides from 0 to 4 seconds of thrust.

Three firings were made in heavy-wall 6-inch motor hardware to demonstrate this concept. Ignition and operation of the hybrid grain was satisfactory. With proper timing of the oxidizer flow, the transition from solid to hybrid operation was indicated by a small dip in the pressure trace.

The information obtained from the preliminary evaluation, supplemented by earlier hybrid fuel regression rate data, was used to design a motor suitable for flight test. The combustion chamber was made in two sections for ease in casting and assembly of the motor. The injector orifices will have either full or hollow cone spray patterns depending on initial test results. The inert motor weight is approximately 25 pounds while the propellant adds 11 pounds—6 hybrid fuel and 5 solid propellant. Four firings have been made with the tandem motor hardware.

The results of this program will appear in a special report in the last quarter of the year.

Appendix A

Table of Nomenclature

$\overline{F}_b$	=	the average thrust over the thrust burning time
F^0_{125}	=	specific impulse corrected to 125 psia chamber pressure, optimum expansion ratio at sea level atmospheric pressure (14.7 psia), and 0° nozzle divergence angle.
F^0_{1000}	=	specific impulse corrected to 1000 psia chamber pressure, optimum expansion ratio at sea level atmospheric pressure (14.7 psia), and 0° nozzle divergence angle
I	=	total impulse of motor or phase of burning.
I_{spd}	=	specific impulse delivered at operating conditions.
K_m	=	$S_m/\overline{A}_t$, where S_m is an integral average surface area and $\overline{A}_t$ is the arithmetic average of throat area before and after burning.
$\dot{m}$	=	mass discharge rate
M_f	=	mass of fuel burned
M_o	=	mass of oxidizer injected
M_p	=	mass of propellant burned
o/f	=	ratio, mass of oxidizer injected to mass of fuel burned
$\overline{P}_b$	=	average pressure over the burning time
$\overline{r}_b$	=	average burning rate over the burning time
t_b	=	web burning time
η	=	combustion efficiency, ratio of F^0_{125} to theoretical specific impulse at same conditions.
$\dfrac{\int P_b\,dt}{\int P_t\,dt}$	=	ratio of the pressure integral over the burning time to the total pressure integral.

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